Characterization of Spray and Combustion Processes of Biodiesel Fuel Injected by Diesel Engine Common Rail System

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Abstract

The influence of injection pressure up to ultra-high value of 300 MPa , nozzle hole diameters of 0.16 and 0.08 mm and fuel properties such as boiling point, cetane number and oxygen content on spray, ignition and combustion characteristics of biodiesel fuel in diesel engine were investigated. Biodiesel from palm oil source (BDF) and for comparison the JIS #2 diesel fuel were utilized. The Mie-scattering technique was used for characterizing the evaporating spray formation processes while the OH chemiluminescence technique was used to determine the ignition and the lift-off length of the combusting flame. Furthermore, the two color pyrometry was applied to study the soot formation processes. The results obtained indicated that due to higher boiling point, the BDF produced longer liquid phase length as compared to diesel. It was observed that the ignition region was larger for the 0.16mm nozzle as compared to the 0.08 mm. Due to the enhanced mixing processes, ignition delay decreased as the injection pressure increased from 100 to 300 MPa respectively and also by reducing the nozzle hole diameter to 0.08 mm. Higher cetane number and oxygen content of the BDF facilitated shorter ignition delay as compared to diesel. The percentage stoichiometry air entrained increased by decreasing the nozzle hole diameter. The BDF flame produced shorter lift-off length and lower percentage stoichiometry air. Under higher injection pressures and decreasing nozzle diameter, the BDF produced less soot as compared to diesel. The fuel oxygen content in the biodiesel fuel played a greater role in the soot formation processes.

Keywords: Biodiesel Fuel; Diesel Engine; Spray; Ignition; Combustion

1. INTRODUCTION

Due to environmental concerns and the rising cost of fossil fuels such as diesel, the search for alternative fuels like biodiesel has attracted more attention. Renewable fuels such as biodiesel continues to be of interest to achieve a sustainable energy economy thus reducing the dependence on fossil fuel utilization. It was further stated that the use of renewable transportation fuels is increasing and a national standard of 5 % in the United States has been proposed in energy-related legislation [1]. The fuel and energy crises of late 1970's and early 1980's as well as accompanying concerns about the depletion of the world's non-renewable resources provided the incentives to seek alternatives to conventional, petroleum-based fuels. Biodiesel fuel is an environmentally clean and renewable energy source. It is usually produced from animal fats or vegetable oils by the trans-esterification reaction. The oxygen content, which is about 11–15 wt percentage, makes biodiesel to enhance the combustion process and reduce pollutant emissions from the diesel engine [2]. Biodiesel as an alternative fuel in diesel engines has a great potential of reducing noxious emissions such as CO, CO_2, HC, PM, SO_x and PAH [3]. The major threat facing the use of biodiesel in diesel engine is the formation and control of NO_x emission. This is because NO_x is closely related to the oxygen concentration in the biodiesel fuel. To this end, it has been proposed that the addition of cetane-improving additives and the decrease in the bulk modulus of biodiesel can be potential ways of decreasing the NO_x emissions. Also by applying early injection timing, the NO_x emission can be reduced drastically [4]. Numerous research works to mention a few have been done on the combustion characteristics of biodiesel fuel in diesel engine [5-8]. Furthermore, recent works on the impact of high injection pressure and micro hole nozzle as effective methods of improving spray atomization and mixture preparation processes of diesel fuel in reducing particulate matters have been reported [9-13]. However, little or no significant work has been done on the role of injection pressure up to ultra-high level and micro-hole nozzle diameter size on the biodiesel spray, combustion, and soot formation characteristics using the constant volume vessel. Therefore, this study tends to focus on experimental study of spray, combustion and soot formation processes of biodiesel fuel spray injected by a common rail injection system in a quiescent constant volume vessel. The role of high injection pressure up to an ultra high value of 300 MPa and nozzle hole diameter up to micro hole of 0.08 mm diameter are to be investigated. Also the influence of some of the biodiesel properties such as viscosity, distillation temperature, oxygen content to mention a few on spray and combustion characteristics need to be clarified.

2. EXPERIMENTAL DETAILS

2.1 Experimental Apparatus and Methods

Experiments were conducted under simulated quiescent conditions in a constant-volume vessel. Figure 1 shows a schematic diagram of the direct photography system for spray and combustion experiments. As shown in Fig. 1, the constant volume vessel can produce typical thermodynamic conditions in the combustion chamber of a diesel engine. Description about this constant volume chamber can be found in previous works by the authors [14]. A manually operated high-pressure generator (High Pressure Equipment Co. model 37-5.75-60) as shown in Fig. 1 was used to generate injection pressure up to 300 MPa in the common rail. Two nozzle hole diameters of 0.08 mm (micro-hole nozzle) and 0.16 mm were utilized in the course of the experiment. The injector driver electronically controlled the injector, while the common rail pressure was measured with a pressure transducer. A pulse/signal generator (Stanford Inc., DG535) was used to synchronize the operation of the CCD camera and injection system. In order to obtain spray images under evaporating conditions, a xenon lamp and two reflecting mirrors were utilized to illuminate the fuel spray inside the vessel. Images were acquired using the Mie-scattering technique. The OH chemiluminescence technique was also used to detect the auto-ignition site and also determine the flame lift-off length. In understanding the soot formation process, the two color pyrometry technique was utilized to provide the flame structure and KL factor to characterize the soot concentration. Figure 1 also shows the experimental arrangement for the spray, OH chemiluminescence and the two color pyrometry imaging. The difference is that there was no illumination for the OH chemiluminescence and two color techniques. A high speed video camera (FASTCAM-APX RS, Photron Corp.) was employed to take the direct photography images of sprays. For the spray, the camera was equipped with a lens (Nikon, 70-210 mm, f/4-5.6). A frame rate of 10,000 fps (frames per second), an exposure time of 1/10000 sec, a resolution of 512 x 512 pixels and an aperture of f/4.0 were utilized to image the evaporating spray. With the aid of the UV-Nikkor lens (Nikon, 105 mm, f/4.5) attached to an image intensifier (LaVision Inc., HS-IRO), the OH chemiluminescence images were captured. OH band-pass filter of wavelength 313 nm (10 nm FWHM) coupled to the image intensifier was used to observe the OH chemiluminescence. In order to acquire clear images without saturation, the OH image intensifier gain and gate were set to optimum values of 70 and 50 μs respectively. For the two color pyrometry images, a visible lens (Nikon, 105mm, f/4.5) was coupled to the camera. The two color system was calibrated using a tungsten lamp (Polaron Components) before it was used to capture two raw identical flame images at wavelengths of 650 and 800 nm (10 nm FWHM). The Thermera HS4 software (Mitsui Optronics, version 4.61) was used to process the captured raw image data obtained from the two wavelengths, thus generating two-dimensional and line-of-sight false-color maps of soot concentration. The same frame rate, resolution and exposure time like the evaporating spray, were used to capture the two color pyrometry images. To avoid saturation in the two color images, the aperture was changed to f/8.0. In the course of the experiments 4 shots of fuel injections were made in order to avoid bias in the data recorded. In eliminating noise from the images which could contribute errors in the data, imaging processing which involves subtracting the captured image from a background image was carried out using in house commercial software. The high speed video camera (FASTCAM-APX RS, Photron Corp.) operates under an 8 bit dynamic range having a maximum intensity of 256. Therefore for the processing of the Mie-scattered spray and OH chemiluminescence combustion images, an optimum threshold intensity value of 20 (i.e. 8% of the maximum intensity) was set in order to get the edge of the subtracted image. This implies that every pixel whose digital level exceeds the threshold value will be considered as image.

2.2 Experimental Conditions

The experimental conditions were determined by the real engine conditions. An ambient density of 15kg/m^3 was used to simulate engine conditions at a crank angle of -10 °ATDC. Biodiesel fuel from palm oil source (BDF) and for comparison, JIS #2 diesel were utilized in the experiments. For both evaporating spray and combustion experiments the ambient temperature and pressure were maintained at 885 K and 4.0 MPa in the constant volume vessel. Nitrogen an inert gas which has similar properties like air was utilized for the evaporating spray experiment to create a non reactive environment. Table 1 shows the list of the experimental conditions, while Table 2 presents the main properties of the two fuels.

3. RESULTS AND DISCUSSION

3.1 Evaporating Spray Characteristics

Figure 2 presents the evolution of the spray under evaporating conditions. The start of injection (SOI) was determined from the frame rate selected as stated earlier i.e. 10,000 fps. Since the fuel injection processes and camera image capturing were controlled using the pulse/signal generator (Stanford Inc., DG535), the first appearance of spray in the frame was taken to be the start of injection energizing (SOE). Due to the settings on the pulse/signal generator (Stanford Inc., DG535), the first appearance of spray was detected between 0.2 to 0.3 ms ASOE (after start of energizing). Therefore extrapolation was done to get the actual start of injection (SOI) of the spray. This method of extrapolation implies obtaining an approximate time of start of injection (SOI) when the spray has a length of 0 mm i.e. no appearance of spray in the frame. The timing that is now obtained when the spray length is 0 mm is now used to determine the actual time for the appearance of the first visible spray image. As shown in Fig. 2, as time proceeds, under the influence of decreasing nozzle hole diameter and increasing injection pressure the liquid phase length became shorter. At 100 MPa, by decreasing the nozzle diameter to 0.08 mm, the liquid phase length decreased considerably. The rate of the decrease in the liquid phase length was further enhanced under the combined effect of the 300 MPa ultra-high injection pressure and 0.08 mm micro-hole nozzle. At higher temperatures, under increasing injection pressure and decreasing nozzle hole diameter, atomization is improved thus enhancing the surface evaporation of the spray and the movement of ambient gas by its momentum leading to shorter liquid phase spray tip penetration. Furthermore, as presented in Fig. 3, after an initial development period, the tip of the liquid phase fuel region stops penetrating and fluctuates about a mean axial location as a result of turbulence. At all injection pressures, the BDF produced longer liquid phase lengths as compared to the diesel. This implies that the diesel fuel evaporated more than BDF. There is the tendency that the higher boiling point of biodiesel which is characterized by the distillation temperature, T90 as stated in Table 2, could have initiated the longer liquid length penetration. This phenomenon was observed in previous works on liquid phase penetration length visualization [3, 15]. Fuels with higher boiling point tend to possess lower volatility. Hence, due to the high boiling point property, BDF is less volatile compared to the diesel fuel. As a result of less volatility, BDF produced longer liquid phase length as compared to diesel. Thus, the energy required to heat and vaporize a lower volatility fuel is higher for a given set of conditions [15, 16]. Since the entrainment rate of energy into the spray is limiting the vaporization process, the requirement for more energy to heat and vaporize the less volatile fuel translates to a longer spray entrainment length to supply the additional energy, and therefore, to a longer liquid length.

Pastor et.al [17] reported that biodiesel blends has a great influence on the liquid phase length. As obtained in their work, liquid phase length tends to increase as the content of the biodiesel in the fuel blends decreases. Hence by comparing the diesel (i.e. 0% biodiesel content) and BDF (i.e. 100% biodiesel content) liquid lengths, similar result as observed by [17] was achieved. On the other hand, by downsizing the nozzle hole diameter to 0.08 mm, there is a drastic reduction in the liquid phase length of the evaporating sprays. It is obvious that the nozzle hole diameter has a greater effect on the liquid phase length as compared to the injection pressure. As confirmed by Siebers [15] and Myong et.al [16], injection pressure has less effect on the liquid phase length. The non-significance in the liquid phase length of the evaporating spray under increasing injection pressure could be as result of the cancelling out phenomenon of the increase in the liquid phase penetration and the faster atomization with mixing effect.

3.2 Auto-Ignition Process

Figure 4 shows the flame development of the combusting fuels from the auto ignition period to the time when the flame profile was stable At 100 MPa, as compared to the 0.08 mm micro hole nozzle, a relatively large ignition region was produced by the 0.16 mm nozzle, which suggests that the ignition could have occurred at simultaneously at multiple points of the spray. As the nozzle hole diameter decreases, the region of the auto-ignition decreased. The auto-ignition location for the BDF is a bit upstream compared to the diesel fuel. At an increasing injection pressure up to ultra-high level of 300 MPa, the spray velocity increases thus pushing the auto-ignition location farther downstream with time. Also, Fig. 5 presents the ignition delay of the BDF and diesel respectively under injection pressures of 100, 200 and 300 MPa and nozzle hole diameters of 0.08 and 0.16 mm. Since the same frame rate was used to obtain the spray and combustion processes, therefore, the extrapolated time for the spray images was adopted in obtaining the ignition delay. From the analyses, irrespective of the nozzle hole size, ignition delay was shortened as the injection pressure increased from 100 to 300 MPa. Also, at all injection pressures, ignition delay was shortened by decreasing the nozzle hole diameter from 0.16 to 0.08 mm. Irrespective of the fuel type, the combined effect of the 300 MPa ultra-high injection pressure and the 0.08 mm micro-hole nozzle further made the ignition delay to be shortened. The shortening in the ignition delay could be attributed to the enhanced mixing achieved at increasing injection pressure and decreasing nozzle hole diameter. Furthermore, as investigated by [18], one of the factors that could affect ignition delay and subsequent combustion processes is the fuel cetane number. BDF has higher cetane number as presented in Table 2 and this could have facilitated its shorter ignition delay when compared to diesel. Another factor that could be responsible for the shortening of the ignition delay could also be the fuel oxygen content [19]. Comparing with diesel, BDF has a shorter ignition delay because of its higher oxygen content.

3.3 Flame Lift-Off Length

After auto-ignition processes, the flame progresses downstream and then stabilizes at a quasi-steady location significantly downstream of the injector tip. As depicted in Fig. 5 with an arrow, the distance from the injector tip to the initial quasi-steady flame location is referred to as the flame lift-off length. A graphical expression for the lift-off length for BDF and diesel is presented in Fig. 6. Irrespective of the nozzle hole size, as injection pressure increases, the lift-off length increases linearly for the two fuels. This could be attributed to the higher spray velocities which arise under the influence of increasing injection pressure thus pushing the initial combustion zone farther downstream. Furthermore, at all injection pressures, decreasing the nozzle hole diameter to 0.08 mm, led to decrease in the lift-off length. The main factor for this was the lower spray velocity by the micro hole nozzle. At all injection pressures and nozzle hole diameters, the BDF produced shorter lift-off lengths as compared to the diesel fuel. Previous results showed that fuels with shorter ignition delays have shorter lift off length [20, 21]. Hence, the same effect holds for the BDF as compared to diesel. By comparing with previous works [22], there is the tendency that injection pressure will have more effect on the lift-off length as compared to the nozzle diameter.

3.4 Percentage Stoichiometry Air Entrained Upstream of Lift-Off Length

At the upstream of the lifted flame, air is usually entrained into the fuel. Hence, fuel air- mixing usually occurs prior to the initial combustion zone. Based on the previous knowledge on the schematic idealized model fuel jet by Naber and Siebers [23], the percentage stoichiometry air entrained upstream of the lift flame i.e. lift-off length could be estimated using the expression for the axial variation of the cross sectional average equivalence ratio, $\overline{\phi}$, in a quasi-steady non reacting fuel jet. The reciprocal of the equivalence ratio when multiplied by 100 gives an expression for the air entrained up to the lift-off location as a percentage of the total air required to burn the fuel being injected. Therefore, the estimated air entrainment upstream of the lift-off length in terms of the percentage of stoichiometric air, $\zeta_{st}(\%)$ as redefined by Siebers [24] can be expressed as;

$$\zeta_{st}(\%) = 100\left[\left(\sqrt{1+16\left(L_o/x^+\right)^2}-1\right)\Big/2f_s\right] \qquad (1)$$

Where,

L_o is the experimental lift-off length, x^+ is the characteristics length scale for the fuel jet defined, f_s which is the stoichiometric air fuel ratio by mass was calculated using the Carbon, Hydrogen, and Oxygen contents as shown in Table 2. It has estimated values of 14.71 and 12.61, for diesel and BDF. In estimating $\zeta_{st}(\%)$, details about the parameters needed to obtain x^+ has been described in previous work by the authors [14].

Figure 7 presents the effect of the injection pressure and nozzle hole diameter on the percentage of stoichiometric air entrained upstream of the lift-off length. As a result of improvement in atomization and mixing processes the percentage of stoichiometric air entrained upstream of the lift-off length increased under the influence of decreasing nozzle diameter and increasing injection pressure. Irrespective of the fuel type, the combined effect of the 300 MPa ultra-high injection pressure and the 0.08 mm micro-hole nozzle further improved atomization hence more air was entrained upstream of the lift-off length. Since the BDF exhibited shorter lift-off length as compared to diesel, the percentage stoichiometric air entrained by the BDF is lower compared at increasing injection pressure and decreasing nozzle diameter. The BDF entrained less percentage stoichiometric air due to its poor atomization which affected the lift-off length.

3.5 Integrated KL Factor

The temporal variation of the line-of-sight and false-color maps of the KL factor processed images obtained from two raw images with wavelengths 650 and 800 nm respectively are presented in Fig.8. As the nozzle diameter reduced from 0.16 to 0.08 mm and injection pressure increased from 100 to 300 MPa, the flame area reduced considerably. The reduction in the flame area implies soot reduction. Information obtained on the two color scale legend which describes the soot levels reveals that as the nozzle diameter reduced to 0.08 mm, the soot level decreased considerably with the BDF flame producing less soot as compared to diesel flame. Irrespective of the fuel type, no soot incandescence was detected under the combined influence of the 300 MPa ultra-high injection pressure and 0.08 mm micro-hole nozzle. Figure 9 presents the temporal variations of the integrated KL factor for the two fuels. The integrated KL factor gives the overall or total soot quantity information in a flame at a particular time. As shown in Fig. 9, for the 0.16 mm nozzle, at the 100 MPa injection pressure, in respective of the fuel type, the integrated KL factors increase gradually, reached a peak value and then decreased with time. The rise of the integrated KL values up to the peak level characterized the soot formation processes while the decreasing integrated KL values could be referred to as soot oxidation processes. The soot formation continues to be dominant over soot oxidation after the end of injection (1.5 ms ASOI) for several milliseconds. At about 2.3 ms ASOI (0.8ms AEOI), the KL factor starts decreasing downwards, signifying the onset of soot oxidation. At the 100 MPa injection pressure, there is no much significant difference in the soot integrated KL factor trends for the BDF and diesel. It can be observed that the soot emergence timing for the BDF is earliest as compared to the diesel. This could be an indication that the start of soot formation is dependent to some extent on the start of ignition By increasing the injection pressure to 200 MPa, there is a decrease in the BDF soot quantity but the KL factor for diesel did not change significantly just like the previous results at 100 MPa. At the 300 MPa, the integrated KL factors for the BDF reduced significantly to the lowest compared to what was obtained at the 100 MPa injection pressure. Also, the diesel flame at 300 MPa achieved a significant change in the integrated KL factor. At the 100, 200 and 300 MPa injection pressures, irrespective of the nozzle size, the time taken for the soot oxidation process was shorter for the BDF as compared to diesel fuel. Furthermore, at a higher injection pressure of 300 MPa, the BDF recorded a lower KL factor as compared to diesel. The soot residence time which is characterized by the duration between the start of soot inception and the start of soot oxidation reduced as the injection pressure increased to 300 MPa. This implies that the rate at which soot formation could be reduced under increasing injection pressure. By downsizing the nozzle hole diameter to 0.08 mm, at the 100 MPa, the soot levels for the two fuels decreased significantly with the BDF producing less soot as compared to diesel. At the 200 MPa, the soot level for the two fuels reduced significantly more than what was obtained by the 0.16 mm nozzle the 300 MPa injection pressures. As reported earlier, no soot incandescence was detected by the two color system under the influence of the combined effect of the ultra high injection pressure of 300 MPa and micro-hole nozzle of diameter 0.08 mm. This implies that the combined effect of the ultra high injection pressure and micro-hole nozzle of diameter enhanced atomization strongly and this further led to a drastic soot reduction in the flames generated by the fuels.

3.6 Correlation of Air Entrained Upstream of Lift-Off Length and Fuel Oxygen Content with Soot Formation

From the previous sections, soot formation for the two fuels decreased under the influence of increasing injection pressure and decreasing nozzle hole diameter. This phenomenon could be attributed to the proper spray atomization processes which enhanced the air entrained thus promoting mixing effect. In the course of combustion of the fuels, air is usually entrained upstream of the lift-off flame. The influence of the air entrained in terms of the percentage stoichiometric air on the net soot formed at all injection pressures using the 0.08 and 0.16mm nozzles are presented in Fig. 10. For the BDF and diesel flames, as the percentage stoichiometric air entrained increases, the integrated KL factor for the soot formed decreased under increasing injection pressure and decreasing nozzle hole diameter. As shown in Fig. 10 the increasing percentage stoichiometric air entrained upstream of the flame lift-off length, tends to produce a less rich central flame reaction zone just downward of the lift-off length. Less rich central flame reaction zone implies less soot formation. Another observation that could be made from Fig. 11 is that despite the smaller percentages of stoichiometric air entrained by BDF, the soot formed is lower compared to that of diesel. This implies that another factor could have contributed to the lower integrated KL factors of the BDF flame. It should be noted that soot formation process does not only depend on physical processes such as the spray atomization, mixing of fuel and entrained air upstream of the lift-off length but also on chemical processes. The chemical bound oxygen content in the fuel undergoing combustion reaction could play an important role on the soot formation process [25]. The overall oxygen molecules in the spray flame needed for soot oxidation could be said to consist of the oxygen content in the fuel molecules (chemical processes) and that in the entrained air upstream of the lift-off length (physical processes). Previous works have revealed the great effect of fuel oxygen content on soot reduction [19, 26-27]. Hence there is the tendency that apart from the air entrained upstream of the flame lift-off length, the oxygen content in the fuel could be a major factor of enhancing soot reduction processes. As presented in Table 2, the BDF oxygen content is 11.1 % as compared to diesel, which is less than 1 % or negligible. It has been reported by [28] that biodiesel fuels have the tendency to provide oxygen in the rich core of the spray during combustion process thus enhancing reduction in the soot formation. Despite the inferior atomization of the BDF spray which led to less air entrained upstream of the lift-off length and also longer liquid phase length (inferior vaporization) which could influenced soot formation, the oxygen in the rich core of the BDF spray could have been responsible for the reduction of soot during the combustion processes. Therefore, the chemical bound oxygen content in the BDF played more significant role on soot formation with increasing injection pressure and decreasing nozzle diameter while the air entrained upstream of the lift-off length had less effect. It can be said that a trade-off between the oxygen in air entrained upstream of the lift-off length and the oxygen content in the fuel controlled the soot formation processes of the BDF at higher injection pressure. Unlike the diesel spray flame, the reduction in soot formation occurred primarily because of the air entrained upstream of the lift-off length under increasing injection pressures and decreasing nozzle diameter.

4. CONCLUSIONS

By conducting experiments under simulated conditions of the D.I. diesel engine, the effect of injection pressure, nozzle size and fuel properties on spray, combustion and soot formation of biodiesel fuels have been investigated. The summary of the results obtained are as follows;

(1) Due to higher boiling point, the BDF produced longer liquid length.

(2) Due to enhanced mixing, ignition delay was shortened as the injection pressure increases to 300 MPa and also by decreasing the nozzle hole diameter to 0.08mm. BDF had shorter ignition delay as a result of higher cetane number and oxygen content.

(3) Under increasing injection pressure and decreasing nozzle hole diameter, BDF produced the shorter lift-off length and less percentage stoichiometry air.

(4) The combined effect of the ultra high injection pressure and micro-hole nozzle of diameter enhanced atomization strongly and this further led to a drastic soot reduction in the flames generated by the fuels.

(5) BDF produced less soot compared to diesel as a result of high oxygen content while the fuel oxygen content in BDF played a greater role in soot reduction as compared to the air entrained upstream of the flame lift-off length.

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Nomenclature

A_n	nozzle cross sectional area
ASOE	after start of energizing
ASOI	after start of injection
ATDC	at the top dead centre
BDF	biodiesel from palm oil
d	orifice diameter
D.I.	direct injection
EOI	end of injection
f_s	stochiometric air-fuel ratio by mass
L_o	lift-off length
x^+	characteristics length scale
$\bar{\phi}$	equivalence ratio
$\zeta_{st}(\%)$	percentage of stoichiometric air